A Framework for Health Monitoring of Structures

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Abstract

This paper summarize a research effort towards the development of an integrated system for monitoring the condition of a civil structure, utilizing advanced sensing, microprocessing, wireless communication and damage diagnosis methods. Specifically, the discussions focus on the following issues: (1) the development of modular wireless vibration sensing, data acquisition and processing units; (2) the development of advanced structural damage assessment procedures; and (3) environmental effects on experimentally obtained modal parameters.

Introduction

The need for rapid assessment of the performance and safety of civil structures such as bridges, control centers, airports and hospitals, among many, has been amply demonstrated during recent natural disasters. In addition, continuous loading and extreme environmental conditions have caused extensive deterioration in our infrastructures. The ability to monitor the structural health of these systems is becoming increasingly important.

The process of implementing a damage detection strategy is referred to as *structural health monitoring*. This process involves the observation of a structure over a period of time using periodically spaced measurements, the extraction of features from these measurements, and the analysis of these features to determine the current state of health of the system. For long term health monitoring, the task is to periodically update information regarding the ability of the structure to continue to perform its desired function. Under an extreme event, such as an earthquake, the objective is to provide in near real time reliable information about the safety of a structure and the performance level of the structure.

The need for a systematic approach for "global" monitoring that can be applied to complex structures has led to the development of methods that examine changes in the vibration characteristics of a structure. Doebling et.al. provided a detailed literature review on many of the current (mostly deterministic) approaches for health monitoring of mechanical and structural systems [3]. Housner et.al. summarized the current research and development specific to civil structures [4].

Most of the research reported have primarily been focused on the development of numerical-based system identification and damage detection procedures.

Central to the damage detection problem is the overall framework for structural monitoring of civil structures – a framework that brings together the hardware and software components to a rational monitoring strategy. The hardware components are to acquire and transmit data and the software components to facilitate the collection and processing of the data. The most commonly used sensor for monitoring vibrations in civil structures is the accelerometer. For the majority of current instrumentation systems, the instrumentation points are typically connected to the centralized data acquisition system through cables. One of the key practical problems is the installation of those systems; installation time could consume over 75% of the total testing time and the labor cost of installing the units easily approach over 25% of the total cost. Maintenance and environmental exposure (such as repeated changes in temperature and humidity, corrosion) are also recurring issues.

There are at least two important issues in the development of a robust health monitoring system for civil structures.

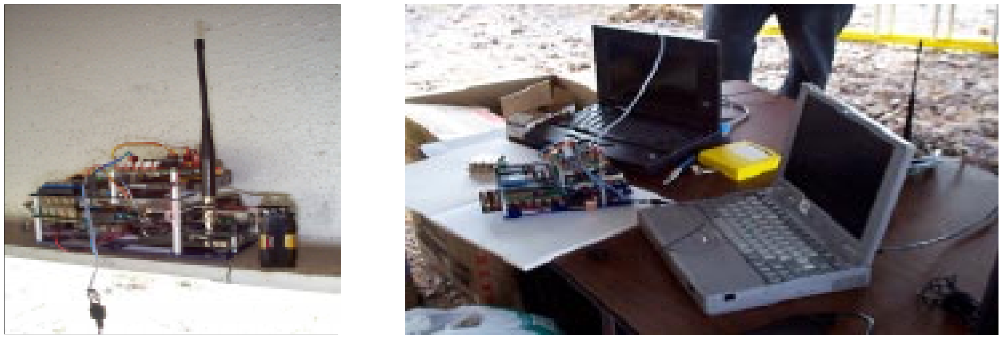
1. Civil structures involve a significant amount of uncertainties. Field studies have shown that environmental effects, such as moisture and ambient temperature can cause frequency changes more than the changes expected from structural damage.
2. For civil structures, it is impractical and too costly to instrument very large number of sensors and actuators. Forced vibration tests are difficult for civil structures in service. Ambient vibration tests are more suitable for civil structures since the test can be conducted under normal operation of structures. One difficulty with ambient tests is to excite and measure higher modes. Only a small number of measurement points and a few fundamental modes are usually available from the vibration tests of civil structures.

This paper describes an integrated vibration-based damage detection framework that includes both the monitoring hardware unit and damage diagnosis procedures. Specifically, three research development efforts are discussed: (1) the development of modular wireless vibration sensing, data acquisition and processing units; (2) the development of structural damage assessment algorithms; and (3) adaptive filtering technique to discriminate temperature effects on the modal parameters.

Instrumentation

There are several technologies that have emerged and created the opportunity to develop a structural health monitoring system that has new configurations and characteristics. In particular, three technologies can potentially contribute significantly toward the possibility of new monitoring systems for civil structures: wireless communication, embedded systems, and miniaturized sensors [2,5].

The requirements of a wireless modular monitoring system (WiMMS) for civil structures have been defined and a prototype was built using economical and commercially available components for monitoring the state of structures (see Fig. 1) [9]. A full scale experiment (with 5 sensor units and a master unit) was conducted at the Alamosa Canyon Bridge in New Mexico for both ambient and forced vibration tests. The units are validated through a comparison with a conventional system conducted in collaboration with researchers at Los Alamos National Laboratory.



(a) WiMMS on Beam Flange (b) Master Control Unit (Sensor and Computer)

Figure 1: Field Installation of the WiMMS Prototype

This proof-of-concept, demonstration system represents a major improvement over existing systems in that data from the sensors are transmitted via a radio modem eliminating the need for extensive cabling, the sensors are small (about 1/5th of the size of currently available commercial sensors) and unobtrusive, and the cost per unit can be substantially reduced. The installation time for the (6 unit) system took about 30 minutes as opposed to over 2-1/2 hours for the installation of the LANL's convention system where most of the time were spent on routing cables and checking electrical connections. The power consumption of the prototype unit involves 3 groups of AA alkaline (18 total) batteries, which provides up to 21 days for awaiting mode and up to 11 hours for continuous operation.

The results from field tests demonstrated many advantages of a wireless, embedded system over a conventional wired monitoring system with a centralized data acquisition. Wireless communication can remedy the cabling problem of traditional monitoring systems as well as reduce the cost associated with it. Embedded systems allow the ubiquity of computational power and data acquisition. Miniature sensors provide compelling performance and unit costs with attractive package sizes and form factors. As the size of sensors and the complete monitoring system decreases, their installation will become increasingly easier and more cost effective. The integrated WiMMS can radically change the practices from using extensive cabling and high cost labor and equipment to the instrumentation of inexpensive wireless embedded systems which can be easily installed, maintained and operated (see Fig. 2).

With a monitoring system based on wireless communication and embedded systems, it is possible to move the data acquisition of the system forward toward the sensors and to perform a portion of the computation locally in an embedded microprocessor and overcome several problems at once. The concept of pushing data acquisition and computation forward is fundamental to the proposed integrated monitoring system and strategy and represents a departure from the conventional instrumentation design and computational strategies for monitoring civil structures. Among the key research issues that need further study include power consumption, packaging and system-wide wireless communication strategies.

Computational Damage Detection Framework

The basic premise of vibration-based damage detection is that the damage will alter the stiffness, mass or energy dissipation properties of a component or a system,

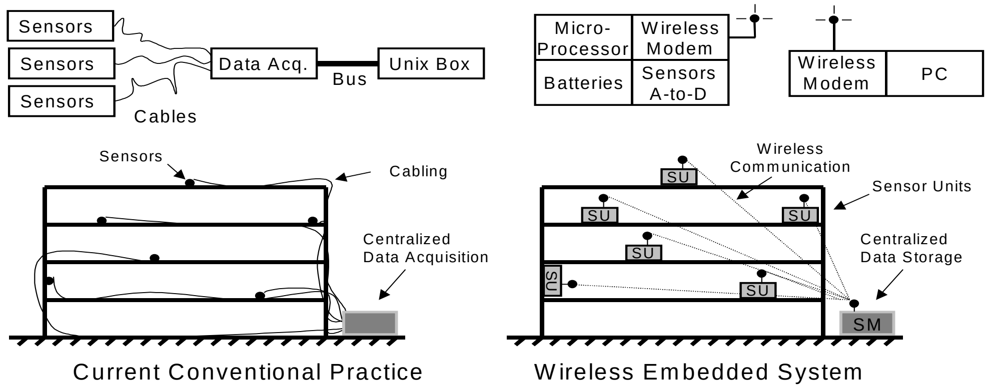


Figure 2: From Conventional System to An Integrated WiMMS

which, in turn, will alter the measured dynamic response. Although the basis for vibration-based damage detection appears intuitive, its actual application poses many significant technical challenges. The most fundamental challenge is the fact that damage is typically a local phenomenon and may not significantly influence the lower-frequency global response of structures that is typically measured during vibration tests.

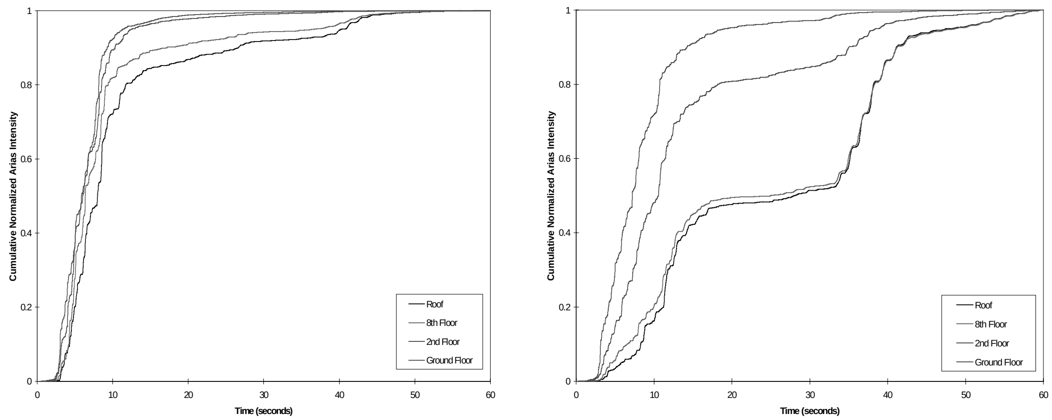
We envision that the overall structural monitoring methodology consists of three basic tasks:

1. *System level screening*: The objective of this task is to quickly identify whether the instrumented structure suffers any deterioration or damage.
2. *Global diagnosis of structures*: The objective of this task is to locate the damage within the sensor resolution being used and to estimate the extent of damage and the level of performance of the structure.
3. *Local damage detection*: With the potential damaged regions identified, visual or localized experimental methods (such as acoustic, ultrasonic, magnetic field, radiographs, eddy-current and thermal field methods) can then be used to evaluate the extent of actual damages.

For the first task, we are interested in rapid damage assessment procedures where computations can be performed locally at the sensor unit (thus increasing the computational throughput). For the second task, statistical based global diagnostic strategies are studied, taking advantage of the capability of the wireless monitoring system for collecting the vibration data in a continual and/or periodic manner.

Rapid Damage Assessment: For extreme events, the damage will likely cause the structure to exhibit nonlinear response. Therefore, the identification of features indicative of nonlinear response can be a very effective means of identifying damage in a structure that originally exhibited linear response. Specific features that indicate a system responding in a nonlinear manner vary widely. For extreme events such as an earthquake, the Arias Intensity is an interesting parameter to consider for condition assessment [9].

In discrete form, the Arias intensity is calculated by squaring and then summing over the duration the acceleration at each location. Using Parseval Theorem, it can be shown that the Arias Intensity is a measure of the kinetic energy in the structure [6]. Over multiple locations, the cumulative Arias Intensity gives a measure of the kinetic energy at each location in the structure as a function of time.



(a) Transverse Direction (b) Longitudinal Direction

Figure 3: Cumulative Normalized Arias Intensities for a 13-Story MR Concrete Frame

For normalization, at each location, the cumulative Arias Intensity is normalized by the value at the end of the time duration, giving a plot between zero and one. By plotting the cumulative normalized Arias Intensity for several locations, a profile of the energy distribution across several locations in a structure can be developed. Since the energy imparted by the ground motion must be dissipated by the structure, and can largely be assumed to be dissipated by viscous damping and absorbed hysteretic mechanisms that imply damage, changes between nearest locations on a structure may indicate accumulation of damage.

As an example, Fig. 3 shows the analysis of an instrumented, 13-story moment resisting concrete frame at Sherman Oaks, CA subjected to the Northridge earthquake [1]. Cumulative normalized Arias intensities are presented for the two orthogonal horizontal directions based on the sensors located on the ground, 2nd, 8th, and roof levels.. In the transverse direction, the general shape is dependent on the ground motion itself, the similarity between the series at each level indicate that serious non-elastic mechanisms are not in effect. On the other hand, the plot of the cumulative normalized Arias Intensity in the longitudinal direction illustrates a significant change in the energy profile between the 2nd and the 8th floors. The damage to the structure was found in the columns of the 2nd story [10].

Global Damage Diagnosis: For damage diagnosis, the task is to determine the possible damage locations and to estimate the extent of damage. To provide a consistent framework for treating data and modeling uncertainties, it is useful to view the damage detection problem using statistical inference. The “model-based” Bayesian probabilistic framework employed is based on statistical (modal) data collected through continuous or periodic ambient or forced vibration measurements [7]. The basic idea is to search for the most probable damage event by comparing the relative probabilities for different damage scenarios, where the relative probability of a damage event is expressed in terms of the posterior probability of the damage event given the estimated (modal) data sets obtained from the vibration test of the structure.

The Bayesian approach has been applied to a (0.5m by 4.9m) steel bridge model tested at the Hyundai Construction Company, Korea (see Fig. 4). Different damage levels with increasing severity are imposed. A series of three test data sets obtained from continuous vibration tests are systematically incorporated into the

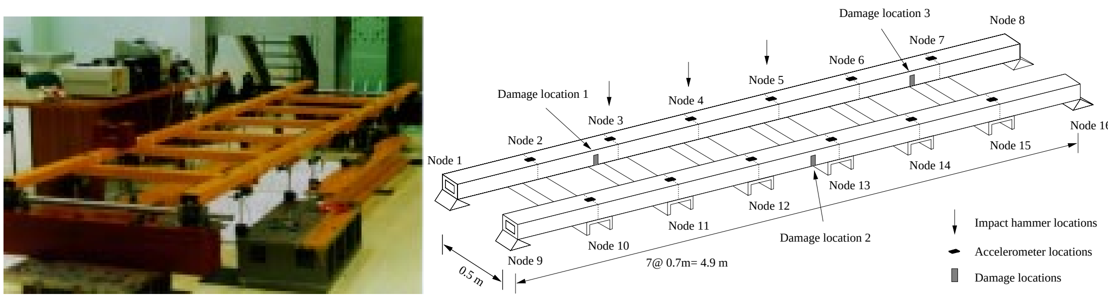


Figure 4: Experimental Study for Damage Detection of a Steel Bridge Model

Table 1: Comparison of Ritz and Modal Vectors for Damage Detection

Case	Damage Locations	Ritz Vectors H_{max}	Ritz Vectors Rank	Modal Vectors H_{max}	Modal Vectors Rank
1	{2}	{2, 3}	1 (2)	{2, 8, 9}	1 (29)
2	{2}	{2, 3}	1 (12)	{2, 8, 12}	1 (46)
3	{2, 11}	{2, 3}	3 (9)	{2, 3, 8}	13 (41)
4	{2, 11}	{2}	3 (3)	{2, 8, 12}	4 (12)
5	{2, 11}	{2, 11}	1 (1)	{2, 11, 12}	1 (9)
6	{2, 6, 11}	{2, 6, 11}	1 (1)	{2, 6, 11}	1 (1)

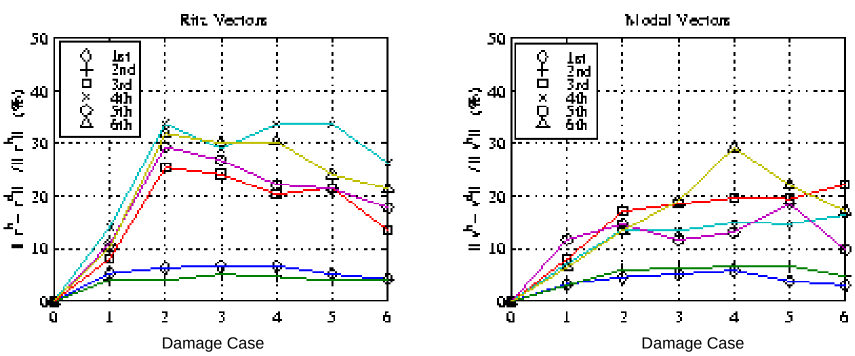


Figure 5: Sensitivity Comparison between Ritz and Modal Vectors

Bayesian framework to progressively improve the diagnostic results. The most common features that are used in vibration-based damage detection are the modal properties such as resonant frequencies and mode shape vectors. We proposed to use load dependent Ritz vectors which can be made more sensitive to various locations and thus provide better information about the global damage diagnosis of a structure.

Table 1 and Fig. 5 illustrate the results obtained for the steel bridge model. In Table 1, the damage locations refer to the member numbers; H_{max} refers to the most probable damage event identified using the branch-and-bound search scheme and “Rank” refers to the ranking of a damage event which includes the damaged member (and the number within parenthesis denotes the rank of the actual damage event). Fig. 5 shows the sensitivity (measured using normalized Euclidean norms between the healthy (h) and the damaged (d) structures) of the Ritz and modal vectors at different damage stages. The Ritz vectors are extracted from a point load applied at node 3. Generally, using different sets of load patterns, load dependent Ritz vectors can be made more sensitive to damage than modal vectors, thus making substructures of interest more observable. Furthermore, the sensitivity analysis can also show

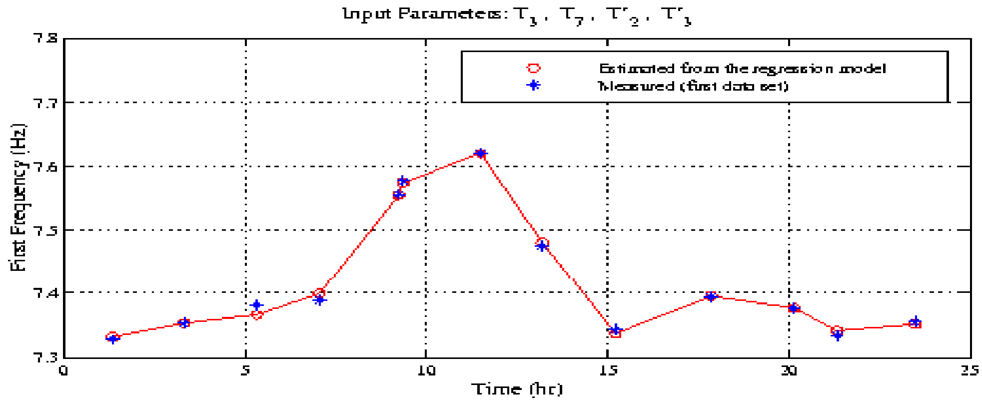


Figure 6: Variation of Natural Frequencies over a 24-hr Period

which sets of load dependent Ritz vectors are more sensitive and thus more appropriate for certain damage locations.

Environmental Effects

Due to the wide variations of the environmental effects on civil structures, it is of fundamental importance that such effects can be detected and discriminated. Sources of variability in the data acquisition process and with the system being monitored need to be identified and minimized to the extent possible. In general, however, all sources of variability can not be eliminated. Therefore, it is necessary to make the appropriate measurements such that these sources can be statistically quantified. We have initiated a study on applying adaptive filtering techniques to discriminate the temperature effects on the estimation of modal parameters [8]. Fig. 6 shows the results of a trained linear adaptive filter applied to the vibration test data collected over a 24-hr period at the Alamosa Canyon Bridge site. Although the results are encouraging, further research is need for complex situation when combination of environmental effects (such as temperature and humidity) are considered. Specifically, appropriate adaptive filtering techniques that can be used to eliminate ambient factors such as temperature, loading and humidity from the recorded vibration signals both at the sensor units as well as the global parameters determined at the central processing unit are needed for field deployment of health monitoring system, particularly for environmentally exposed structures.

Summary

In this paper, we describe a research effort towards the development of an integrated structural health monitoring framework. The results from field tests demonstrated many advantages of a wireless, embedded system over a conventional wired monitoring system with a centralized data acquisition. For rapid assessment, an initial study on the use of Arias Intensity has been performed. For damage diagnosis, a Bayesian-based probabilistic computational framework, using modal and Ritz vectors, has been developed. In additon, a linear adaptive filtering technique has been developed to discriminate temperature effects on the modal parameters. Research efforts continue to improve both the hardware and software components of the framework and to develop a robust health monitoring system for civil structures.

Acknowledgement

This research was partially sponsored by the National Science Foundation under Grant No. CMS-95261-2. The authors would like to acknowledge the collaboration with Prof. Teresa Meng of Electrical Engineering at Stanford University and Dr. Charles Farrar and Scott Doebling of Los Alamos National Laboratory.

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